Year: 2019

The 10Be deglaciation chronology of the Göschenertal, central Swiss Alps, and new insights into the Göschenen Cold Phases

Boxleitner, Max ; Ivy-Ochs, Susan ; Egli, Markus ; Brandová, Dagmar ; Christl, Marcus ; Dahms, Dennis ; Maisch, Max

Abstract: The Göschenertal (Göschenen valley) is the type locality of the so-called Göschenen Cold Phases I (3–2.3 ka) and II (1.8–1.1 ka). According to earlier studies, these Late Holocene climatic cooling periods were characterized by changes in vegetation and pronounced glacier advances. As a peculiarity, the Göschenen Cold Phase I was thought to be connected to a local surge-type advance of the Chelengletscher (Chelen glacier) – an exceptional event of unparalleled dimension in the European Alps. Based on cosmogenic 10Be exposure ages from moraine boulders, we investigated the local glacier chronology. In contrast to former research, moraines at different positions within the Göschenen valley (central Swiss Alps) have been dated to the Younger Dryas and the Early Holocene. This questions the applicability of palaeo-Equilibrium Line Altitude (ELA) calculations for stadial attributions without additional numerical age constraints. Furthermore, we have found compelling evidence that the proposed non-climatic glacier advance attributed to the Göschenen Cold Phase I did not occur. The present results, along with a reappraisal of the original study, question the scientific reliability and the glaciological definition of the Göschenen Cold Phases as glacier advances that clearly exceeded the Little Ice Age positions. While our data do not exclude potential changes in climate and vegetation, we nonetheless show that the Göschenen Cold Phases are not suitable as reference stadials in the system of Alpine Holocene glacier fluctuations.

DOI: https://doi.org/10.1111/bor.12394

Originally published at:
Boxleitner, Max; Ivy-Ochs, Susan; Egli, Markus; Brandová, Dagmar; Christl, Marcus; Dahms, Dennis; Maisch, Max (2019). The 10Be deglaciation chronology of the Göschenertal, central Swiss Alps, and new insights into the Göschenen Cold Phases. Boreas, 48(4):867-878.
DOI: https://doi.org/10.1111/bor.12394

The ^{10}Be deglaciation chronology of the Göschenertal, central Swiss Alps, and new insights into the Göschenen Cold Phases

MAX BOXLEITNER, SUSAN IVY-OCHS, MARKUS EGLI, DAGMAR BRANDOVA, MARCUS CHRISTL, DENNIS DAHMS, AND MAX MAISCH

Boxleitner, M., Ivy-Ochs, S., Egli, M., Brandova, D., Christl, M., Dahms, D. & Maisch, M.: The ^{10}Be deglaciation chronology of the Göschenertal, central Swiss Alps and new insights into the Göschenen Cold Phases. *Boreas.*

The Göschenertal (Göschenen valley) is the type locality of the so-called Göschenen Cold Phases I (~3–2.3 ka) and II (~1.8–1.1 ka). According to earlier studies, these Late Holocene climatic cooling periods were characterized by changes in vegetation and pronounced glacier advances. As a peculiarity, the Göschenen Cold Phase I was thought to be connected to a local surge-type advance of the Chelengletscher (Chelen glacier) - an exceptional event of unparalleled dimension in the European Alps. Based on cosmogenic ^{10}Be exposure ages from moraine boulders we investigated the local glacier chronology. In contrast to former research, moraines at different positions within the Göschenen valley (central Swiss Alps) have been dated to the Younger Dryas and the Early Holocene. This questions the applicability of palaeo-ELA (Equilibrium Line Altitude) calculations for stadial attributions without additional numerical age constraints. Furthermore, we have found compelling evidence that the proposed non-climatic glacier advance attributed to the Göschenen Cold Phase I did not occur. The present results, along with a reappraisal of the original study, question the scientific reliability and the glaciological definition of the Göschenen Cold Phases as glacier advances that clearly exceeded the Little Ice Age positions. While our data do not exclude potential changes in climate and vegetation,

we nonetheless show that the Göschenen Cold Phases are not suitable as reference stadials in the system of Alpine Holocene glacier fluctuations.

Max Boxleitner (Corresponding author: max.boxleitner@geo.uzh.ch), Department of Geography, University of Zurich, Winterthurerstrasse 190, Zurich, 8057, Switzerland; Susan Ivy-Ochs, Laboratory of Ion Beam Physics, ETH Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland; Markus Egli, Department of Geography, University of Zurich, Winterthurerstrasse 190, Zurich, 8057, Switzerland; Dagmar Brandova, Department of Geography, University of Zurich, Winterthurerstrasse 190, Zurich, 8057, Switzerland; Marcus Christl, Laboratory of Ion Beam Physics, ETH Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland; Dennis Dahms, Department of Geography, University of Northern Iowa, Cedar Falls, USA; Max Maisch, Department of Geography, University of Zurich, Winterthurerstrasse 190, Zurich, 8057, Switzerland;

Sequences of moraines consecutively deposited along valley profiles are always a discontinuous and incomplete archive of glacial activity. Provided that the topography renders deposition and preservation of moraines possible, only pronounced glacier re-advances or periods of stable terminal positions of the glacier tongue lead to the formation of recognizable moraines. Moraine remnants deposited during warm interstadial periods with reduced glacier extents are usually erased or overprinted during subsequent glacier advances. This was frequently the case during the Holocene: Glaciers throughout the European Alps lost large parts of their mass, following the transition from the Younger Dryas (YD) to the Early Holocene (e.g. Ivy-Ochs *et al.* 2009). Subsequently, evidence of small-scale Holocene advances was overprinted in many Alpine glacier forefields during the Little Ice Age (LIA; ~ AD 1350–1850) (e.g. Joerin *et al*. 2006; Le Roy *et al*. 2015; Kronig *et al*. 2018) that reached its maximum in some instances around AD 1820, but most frequently around AD 1850 (Grove 1988; Holzhauser & Zumbühl 1988; Holzhauser *et al*. 2005; Wanner *et al*. 2008; Solomina *et al*. 2015). These distinct moraines are often the result of several glacier advances with similar dimensions resulting in a superposition of moraine deposits (Joerin *et al. 2006).*

Cosmogenic surface exposure dating has revealed that moraines of many Alpine valleys have been deposited with a significant temporal gap of several thousand years between moraines originating from the Early Holocene and the so-called 1850-moraines (Ivy-Ochs *et al*. 2009; Moran *et al*. 2016, 2017).

^{10}Be dating can be a helpful method to investigate moraine sequences of glaciers that reacted to small-scale Holocene climate fluctuations and produced moraines outside of the LIA extents (e.g. Schimmelpfennig *et al*. 2012, 2014; Moran *et al*. 2017; Le Roy *et al*. 2017). But usually glacier extents were smaller during most of the Holocene than during the LIA and often there are no moraines preserved that could be dated. Therefore, existing information about Holocene glacier fluctuations is mainly based on the dating of subfossil trees and peat exposed in modern glacier forefields (e.g. Joerin *et al*. 2006; Le Roy *et al*. 2015). Further palaeo-climatic information has been gained through the analysis of pollen samples from peat bogs (e.g. Burga *et al*. 1998), identification and dating of covered palaeo-soils in stacked LIA moraines (e.g. Schneebeli & Röthlisberger 1976; Renner 1982) and the analysis of lake sediments (e.g. Holzhauser *et al*. 2005) and speleothems (e.g. Luetscher *et al*. 2011). On the basis of these different climate proxies and archives only relative changes in glacier length can be inferred, but not absolute maximum positions of former glacier advances.

Radiocarbon dating of wood and peat samples in the forefield of today's shrinking glaciers has led to the conclusion that for most of the Early to the Middle Holocene the glaciers were smaller than during the LIA (Hormes *et al*. 2001; Joerin *et al*. 2006; Nicolussi & Schlüchter 2012). Based on *in situ* cosmogenic $^{14}C/^{10}Be$ dating, similar results have been also obtained in a study of the exposure history of proglacial bedrock in the forefield of the Rhone glacier (Goehring *et al*. 2011). During the Middle Holocene, after the so-called Holocene Climatic Optimum (Renssen *et al*. 2009; Charpentier Ljuungqvist 2011) glaciers started to advance again, most probably as a response to orbital forcing (Wanner *et al*. 2008; Solomina *et al*. 2015). This phase, often called Neoglaciation, has no generally defined onset: In the European Alps there is indication for first glacier advances at ~5 ka and for dominantly favourable conditions for glacier growth after ~3.6 ka until ~ AD 1850 (Leemann & Niessen 1994; Wipf 2001; Nicolussi & Patzelt 2001; Solomina *et al*. 2015; Le Roy *et al.* 2015, 2017; Moran *et al*. 2017).

Evidence for such Late Holocene advances has been found in different regions of the European Alps. The most prominent cold periods in this context are the Löbben oscillation (~3.8–3.4 ka), locally defined through studies of peat bogs in the Maurertal (eastern Tyrol, Austria) (Bortenschlager & Patzelt 1969) and the Göschenen Cold Phases I (~3–2.3 ka) and II (~1.8–1.1 ka) (Zoller *et al*. 1966).

Indication for Löbben-equivalent advances has e.g. been found in the Austrian Alps at Gepatschferner (Nicolussi & Patzelt 2001) and in the Lisenser Längental (Moran *et al*. 2017), in the French Alps at Mer de Glace (Le Roy *et al*. 2015) and in the Swiss Alps e.g. at Tschingelfirn (Wipf 2001) and at Aletschgletscher (Schimmelpfennig *et al*. 2012). Glacier advances around 1–3 ka that were attributed to the Göschenen Oscillations I and II have been reported e.g. from the Grosser Aletschgletscher (Holzhauser 1995), from Tsidjiore Nouve (Schimmelpfennig *et al*. 2012), Steingletscher (King 1974; Schimmelpfennig *et al*. 2014), Triftjegletscher (Kronig *et al*. 2018) and Mer de Glace (Le Roy *et al.* 2015).

In our study of the glacial history of the Göschenertal we address and re-evaluate the local glacier development and in particular the site that led to the definition of the so-called “Göschenen Cold Phases” (Zoller *et al*. 1966). In a previous study of this valley we focused mainly on the evolution of soils and mires after deglaciation (Boxleitner *et al*. 2017). The disappearance of the glacier ice as a starting point for the mire and soil development in the valley has been dated with *in situ* ^{10}Be dating. Prominent lateral moraines (Fig. 1) that indicate a glacier terminal position in today's village of Göschenen are now assigned to the Younger Dryas. We originally assumed that the Göschenen Cold Phase I and II would have left easily recognizable traits, e.g. as pollen signal in the peat cores, but our results could not unambiguously confirm the findings of Zoller *et al*. (1966), although the peat samples partly originate from the same mire (Boxleitner *et al*. 2017). As a follow-up study we have now re-investigated the local geomorphology, calculated palaeo-ELAs (Equilibrium Line Altitude) of reconstructed glacier outlines and dated additional boulders from different moraines with the aim of assessing the local Lateglacial and Holocene glacier development, supposedly including traces of the presumed surge-type glacier advance connected to the Göschenen Cold Phase I as postulated by Zoller *et al*. (1966).

Study area

Geological setting

The Göschenertal is located in the central Swiss Alps (Fig. 1), west of the village of Göschenen (1106 m a.s.l.). The ~15 km long valley is a tributary to the Reusstal, which is the main valley of the canton of Uri that connects the Swiss foreland in the north to the Gotthard Pass region in the south. Within the Göschenertal, ~4 km from its lower terminal, the Voralp valley joins the main valley from the northwest. Further up valley, an artificial lake, the Göscheneralpsee, covers the valley floor since 1960 with a length of ~2.3 km. West of the lake, the Göschenertal splits into the Chelenalp valley continuing to the northwest until it reaches the Chelengletscher and into a valley to the southwest, to the Dammagletscher and its forefield.

The Göschenertal can be subdivided into two geological zones: the lower part, that includes most of the Voralp valley, the catchment of the Dammagletscher and about half of the Chelenalptal, contains mainly the light Aare granite. The upper Chelenalptal and the higher parts of the Voralp are characterized by a mixture of crystalline rocks that belong to the 'northern slate-zone' of the Aare massif (Labhart & Pfiffner 2011; Spillmann *et al*. 2011). Erratics from this area can be easily identified because of their rusty weathering colour (Zoller *et al*. 1966). All sampled boulders in this study were either granites or gneisses (Table 1).

The type locality of the Göschenen Cold Phases

Analyses of pollen samples from peat bogs north of the lake and dates on wood remnants and peat that were found in the course of drilling explorations for the artificial lake resulted in the definition of the Göschenen Cold Phases I and II (Zoller *et al*. 1966). In the drillings on the valley floor, organic material both below and on top of a thick debris layer was found. Based on radiocarbon ages the deposition of the debris was dated to ~2.5 ka. The debris cover was interpreted as moraine material deposited by the Chelengletscher with an assumed terminal position in the area of today's dam. Note that the drill sites are more than 3.5 km down-valley from the LIA moraines of the Chelengletscher (Fig. 1) and that the terrain in between is almost flat with slope of only 1.5–4.8° (Röthlisberger 1969). Since this glacier position exceeded the normal magnitude of Holocene advances, Zoller *et al*. (1966) assumed that it was linked to a pronounced surge-like re-advance probably triggered by an immense rockfall onto a rather extended Chelengletscher. Comparable events in the European Alps have not been previously reported.

Although the Göschenen Cold Phases are often cited as phases with glacier sizes exceeding the LIA, the exact climate-driven extents before the supposed climate-independent advance are unknown at the type locality. The connection between the climatic cooling and the absolute glacier size remains unclear in the original study (Zoller *et al*. 1966). The assumed sudden glacier advance apparently occurred several centuries after the beginning of the Göschenen Cold Phase I (Röthlisberger 1969) and cannot be primarily linked to a climatic deterioration. Although originally described as 'catastrophic glacier advance' that is compared to typical surge glaciers in the Andes and Alaska, the advance in the Göschenertal should rather be described as a singular non-climatic advance than as a classical surge (Zoller *et al*. 1966; Gamper & Suter 1982). According to the original study, the only potential evidence for extended glaciers during Göschenen Cold Phase I is that a certain glacier size, i.e. ice volumes exceeding those of the LIA, would be necessary to explain the presumed low lying glacier terminal position after the assumed surge-like advance.

Unfortunately the original research site of Zoller *et al*. (1966) cannot be re-investigated, because it lies at the bottom of the dammed lake.

Methods

Sampling of morainic boulders for ^{10}Be exposure dating

After analysing historic and modern topographic maps of the Göschenertal and the DEM of the valley, glacial landforms and in particular moraines were in detail examined in the field. Rock samples from suitable boulders were obtained with a battery-powered saw, hammer and chisel. The selection of boulders followed standard criteria (for details see e.g. Ivy-Ochs & Kober 2008). Where possible we took samples in unambiguous geomorphological environments from the top surface of quartz-rich, large (>1 m), flat-topped boulders that showed no obvious signs of post-depositional exhumation, toppling, excessive weathering or exfoliation. Because of the attenuation of cosmic rays, spallation reactions in the rock decrease exponentially with depth. Samples are therefore taken from the uppermost centimetres, where cosmogenic nuclide concentrations are highest (cf. Gosse & Philips 2001). Topographical shielding and inclination of the sample surface were recorded for each sample.

In addition to moraines that indicate a glacier terminal position in the area of today's village of Göschenen (cf. Boxleitner *et al*. 2017), morainic boulders were sampled ~1.5 km up valley from Zoller *et al*.'s research site in the forefields of the Damma- and Chelengletscher (see Fig. 1). According to Zoller *et al*. (1966) these moraines should have been deposited in connection to Göschenen Cold Phase I and/or later. We therefore have here the unique opportunity to re-evaluate the findings of the original study for evidence of the supposed non-climatic glacier advance.

Sample preparation and age calculation

The samples were treated according to in-house standard procedures, described in Boxleitner *et al*. (2017). The measurement of the $^{10}Be/^{9}Be$ ratios was taken with the TANDY Mass Spectrometer of the ETH Laboratory of Ion Beam Physics (Christl *et al*. 2013) against the ^{10}Be standard S2007N, which is calibrated against the 07KNSTD standard (Nishiizumi *et al*. 2007).

The exposure ages of the samples were calculated from the blank corrected ^{10}Be concentrations (blank ratio: (0.007±0.0021) x 10^{-12}) using "the online calculators formerly known as the CRONUS-Earth online calculators" version 2.2 (Balco *et al*. 2008; http://hess.ess.washington.edu/math/) with the Northeastern North America (NENA) ^{10}Be spallation production rate of 3.87±0.19 ^{10}Be atoms $gram^{-1}$ SiO_2 $year^{-1}$ (Balco *et al*. 2009), a ^{10}Be half-life of 1.387±0.012 Ma (Chmeleff *et al*. 2010; Korschinek *et al*. 2010) and the scaling scheme of Lal (1991) and Stone (2000). For the age calculation we used an erosion rate of 1 mm ka^{-1} (André 2002) and applied a rock density of 2.7 g cm^{-3}. Additionally the effect of geometric shielding by surrounding mountains has to be considered for every sample. This was done with an online topographic shielding calculator (http://hess.ess.washington.edu) using the field measurements. The input data for the online age calculation can be found in Table S1.

The NENA production rate seems to be well applicable in the European Alps (Claude *et al*. 2014). The calculation of exposure ages with the global production rates (Heyman 2014; Borchers *et al*. 2016) used in CRONUS version 2.3 would lead to slightly younger ages (~2.5–3%).

Calculation of Equilibrium Line Altitudes

We estimated Equilibrium Line Altitudes (ELAs) and ELA-depressions (ΔELAs) with the Accumulation Area Ratio (AAR) approach and applied a uniform ratio of 0.67 (Accumulation area : ablation area = 2:1) (Meier & Post 1962; Porter 1975; Gross *et al*. 1977; Maisch 1981; Benn & Lehmkuhl 2000). Although other calculation methods exist, we chose this approach to ensure comparability with former research, as this method represents the traditionally used standard for the reconstruction of palaeo-ELAs in the European Alps. 1850-ELAs were calculated for 28 glaciers still existing within the Göscheneralp and the Voralp (Table 2). ELAs and corresponding ΔELAs (in comparison to the 1850-glacier outlines) of older stages were calculated only for glacier positions with moraines that have been dated in this study (Table 2). We based our glacier reconstructions on maps of moraine positions, a digital elevation model and LIA extents shown on historic maps. The reconstruction of glacier outlines was done with Swisstopo online tools (www.map.geo.admin.ch). Values were rounded to the 5 m accuracy level.

Results and discussion

Dating results and interpretation

The dating results are shown in Table 1. All already published exposure ages have been recalculated using the NENA production rate. Here we subsume all the moraines that can be ascribed to the inferred terminal position at the end of the valley (cf. Boxleitner *et al*. 2017) under the term Göschenen stage. This includes the moraines at Bergstaffel (upper Göschenertal, Fig.3), Börtli, Golderen and Börtlistafel. Figure 2 shows the sample locations (Börtli) and exposure ages in the lower part of the Göschenertal. Three samples in this area (Börtli 4, Wandflueseeli 1 and 2) could not be measured successfully, because the samples did not contain enough quartz. The ~2 km long ice margin on the southern side of the valley and the inner left lateral moraine on the northern side (with a house on it) belong to the Göschenen stage. In our earlier study we dated the sample Börtlistafel to an age of 12.0±0.5 ka and Börtli 3 to 9.7±0.6 ka. On the basis of the position within the valley and the clearly older ages derived from other stratigraphically matching boulders attributed to the Göschenen stage, Börtli 3 has been identified as outlier. Another moraine belonging to this stage is preserved on the orographic left side of the valley just below the confluence of the Göschenertal and the Voralp at the Golderen site (not visible from this perspective in Fig. 2; see Figs 1 and 4; cf. Boxleitner *et al*. 2017). A sample from this location yielded an age of 13.1±0.5 ka (Golderen).

In addition to the pronounced Göschenen stage moraine at the Börtli site, there is another outer embankment on the other side of the locally evolved mire, directly at the foot of the slope (Fig. 2). The origin of this landform is not entirely clear; it could either be talus deposits or the result of glacial deposition. Here we took the Börtli 2 sample, which was dated to 6.9 ± 0.4 ka. 50 m above the mire and slightly up-valley we took the Börtli 1 sample from a large block lying at the edge of glacially streamlined bedrock. The position of this boulder on a small plateau on an overall very steep slope suggests that this block was rather deposited at the margin of a former glacier than during a rockfall event. This sample yielded an age of 2.7±0.2 ka. The exposure ages of the Börtli 1 and 2 samples are apparently too young in light of the local stratigraphic succession and the other exposure dating results. If deposited by a former glacier, both samples should be older than the YD-aged Göschenen stage (Boxleitner *et al*. 2017). A reasonable explanation for the young boulder ages is a deposition not by the palaeo-glacier but by rockfall/landslide processes, since the slope above the sampling locations is known to be unstable. In the end, the origin and the depositional age of these two samples remain equivocal.

In the upper part of the Göschenertal we had earlier determined the exposure ages of the samples Bergstaffel 1 and 2 (Fig. 3) from a clear, ~1.5-km-long left lateral moraine. This moraine matches the left lateral moraine preserved at the Börtli site further down valley and also belongs to the Göschenen stage (cf. Boxleitner *et al*. 2017). The recalculated exposure ages of these boulders are 11.6±0.5 ka and 12.4±0.5 ka. On the basis of our dating results, the stratigraphically and geomorphologically defined glacier terminal position at the end of the Göschenertal, the Göschenen stage, can be attributed to the YD. This interpretation is based on the age of the four samples Bergstaffel 1 and 2, Börtlistafel and Golderen, which have been dated to the time range between 11.6 and 13.1 ka. Within uncertainties all these samples overlap with the Younger Dryas. Concerning the available data and the possible resolution of exposure dating due to geological factors like inheritance and exhumation, a more precise age assessment of the Göschenen stage glacier advance is not feasible at this point.

In addition to the samples of the Göschenen stage, we sampled boulders on two stratigraphically younger moraines, one each in the forefield of the Chelengletscher and the Dammagletscher to the west of the Göscheneralpsee. Another sample was obtained uphill of the long left lateral Bergstaffel moraine that surrounds the small lake Bergsee (Fig. 3). All three samples were dated to the Early Holocene. The Göscheneralpsee sample originates from a left lateral moraine deposited by the Chelengletscher and was dated to 9.7±0.7 ka. The moraine is clearly dipping towards the valley floor. This indicates a former terminal position in the western part of today's lake. South of this area we sampled a boulder from a left lateral moraine of the Dammagletscher. The Damma sample yielded an age of 10.5±0.4 ka. The location of the moraine on top of a bedrock ridge and its direction indicate that the Dammagletscher had its terminal position only slightly further down valley at the time of deposition. While the absolute terminal positions of both glaciers remain unknown (further indication could probably lie at the bottom of the lake), the moraine relationships clearly point to Early Holocene glacier terminal positions in a narrow area in the western part of today's lake (Fig. 3). We subsume these terminal positions under the term Göscheneralp stage.

The Bergsee sample was deposited at 10.8±0.3 ka by a small cirque glacier below the Schinstock that today has almost vanished (for this study we name the glacier 'Schinstockgletscher'). From the sequence of moraines in this small separate glacier system it is not clear whether the apparent exposure age of the sample fits the stratigraphic position and thus if this sample has to be attributed to the Göschenen or the Göscheneralp stage. Morainic ramparts outside the dated moraine and clear, younger moraines further up the block- and debris-rich slope indicate that a deposition of this moraine in response to the YD is possible despite the Early Holocene ^{10}Be exposure age. As the long left lateral Bergstaffel moraine further down the slope shows, the small glacier system below the Schinstock did not contribute to the main valley glaciation during the Göschenen stage. Thus, equivalent

YD moraines also have to be located on the slope. We cannot exclude that the Bergsee sample originates from an YD-equivalent moraine, although it has yielded an Early Holocene age (Fig. 3). Here at the Bergsee site, a clear attribution of the moraines to certain stages and deposition ages can only be achieved with additional exposure ages.

In summary, we have dated two different stages of the (de-)glaciation history of the Göschenertal: (1) the Göschenen stage with its terminal position in today's hamlet could be attributed to the Younger Dryas (cf. Boxleitner *et al*. 2017) and (2) glacier terminal positions of the Damma- and the Chelengletscher in the western part of today's lake that we subsume under the term Göscheneralp stage could be ascribed to the Early Holocene (Fig. 4).

ELA reconstruction

The reconstructed 1850-ELA values (Table 2, Fig. 4) range between 2375 m a.s.l. (Nr. 7) and 2850 m a.s.l. (Nr. 20). The spatial position of the ELA as a proxy for the mass balance of a glacier depends not only on regional climate but individually on a whole set of local factors like slope aspect, topography, debris cover and others (cf. Clark *et al*. 1994; Benn & Lehmkuhl 2000; Boxleitner *et al*. unpublished data). In this context the AAR-method has been criticized, because ELAs are determined without considering the hypsometry of a glacier, which might be a crucial factor for a more accurate ELA-calculation (Osmaston 2005; Lukas 2007). Nevertheless, in the European Alps mainly ELA-depressions (Δ-ELAs) calculated with the AAR-approach (2:1 or AAR = 0.67) have been used to compare and correlate undated moraine stages of glaciers among different Alpine valleys (in the research area: Renner 1982). AAR-values therefore still represent the basis for comparison; this method, however, is based on the rather questionable assumption that ELA-depression values in the European Alps vary in a similar way and are primarily controlled by climate. In our dataset of the 1850-ELAs in the Göschenertal we found a remarkable difference of 475 m between the highest and the lowest ELA estimates. This shows the considerable heterogeneity of glacier systems and their reactions under comparable climatic conditions.

The Göscheneralp stage of the Dammagletscher is characterized by an ELA of 2470 m a.s.l., which is only 60 m lower than the 1850-level. The corresponding frontal position of the Chelengletscher in the western part of the Göscheneralpsee (with ice contribution from the Rotfirn and Maasplanggfirn) yields an ELA of 2305 m a.s.l. and a depression of -140 m. Based on interregional comparison of Equilibrium Line Altitude depressions (ΔELAs), Renner (in Spillmann *et al*. 2011) described these two moraines to the west of the lake, in contradiction to Zoller *et al*.'s (1966) attribution to the Late Holocene (Göschenen Cold Phase I), as local versions of the late Lateglacial Egesen stadial. In light of our Early Holocene ^{10}Be ages, also this attribution does not seem entirely accurate.

The dated moraine of the Schinstockgletscher yielded an ELA of 2505 m a.s.l., which is 225 m lower than around AD 1850. This stage corresponds to a ΔELA value between the Göscheneralp stage depressions of the Chelen- and Dammagletscher and the YD-aged Göschenen stage (see below), to which the Schinstockgletscher definitely did not contribute as the moraine configuration at the Bergstaffel site shows. Thus, also the ELA-calculation does not make feasible a clear attribution of this former glacier position to a certain stage.

According to our reconstructions the Göschenen stage glacier has an ELA of 2110 m a.s.l., which results in a corresponding ΔELA of -435 m. Renner (1982) calculated a similar depression value of ~430 m using the d/2-method (Zienert 1965, 1970), but then offered a different interpretation and stadial attribution. Without any direct age constraints, Renner (1982) equated the Göschenen stage, in accordance with the scientific concept of that time, to the Daun of the East Alpine system of deglaciation, which was assumed to be characterized by ELA depressions of -400 m to -500 m (Ivy-Ochs 2015). The definition and presumed old age of the Daun stadial (pre-B/A interstadial) has recently been questioned (Reitner *et al*. 2016). Supporting these findings we now ascribe the Göschenen stage – a former Daun-equivalent – on the basis of exposure dating to the Younger Dryas.

As much as the individual ELAs vary from glacier to glacier, also ΔELAs are subject to noticeable irregularities depending on the above-mentioned initial conditions of each glacier. Without additional evidence (in particular chronological constraints) the AAR-method, the way it is commonly applied in the field of palaeo-glacier reconstruction in the European Alps (AAR = 0.67), is not accurate enough to clearly attribute an undated moraine stage in one glacier system to a known stadial of another glacier system. Several exposure dating studies of the recent past (Moran *et al*. 2016; Reitner *et al*. 2016; Boxleitner *et al*. unpublished data) have shown that comparing only the ΔELAs of completely different localities without age constraints may lead to erroneous results/allocations.

Chronology of the glacier history in the Göschenertal

From our ^{10}Be exposure age-results, we assign the Göschenen stage to the Younger Dryas (Boxleitner *et al*. 2017), whereas the moraines west of the artificial lake, subsumed under the term Göscheneralp stage, are assigned to the Early Holocene (Fig. 4). Comparable ages for similar glacier positions in the region are known from the Meiental (Boxleitner *et al*. unpublished data) and from the forefield of the Steingletscher (Schimmelpfennig *et al*. 2014). Younger Dryas glacier advances and resulting moraines have been dated and described throughout the European Alps (e.g. Ivy-Ochs *et al*. 1996; Kelly *et al*. 2004; Federici *et al*. 2008; Böhlert *et al*. 2011; Bichler *et al*. 2016; Reitner *et al*. 2016). In most cases these advances have been described as equivalents of the Egesen stadial (cf. Ivy-Ochs *et al.* 2009), a term that was originally defined for a moraine stage at a Tyrolian type locality, but then evolved to an Alpine-wide reference stadial (summarized in Kerschner, 2009). Due to their abundance and mostly good preservation, YD moraines are the best studied moraines of the Lateglacial in the Alps.

But particularly in recent years, there has been an increase in evidence of distinct Early Holocene glacier advances (e.g. Kelly *et al*. 2004; Schimmelpfennig *et al*. 2012; Schindelwig *et al*. 2012; Moran *et al*. 2016). Also the moraines that according to Zoller *et al*. (1966) should have been deposited within the context of the Göschenen Cold Phase I glacier advance or later were dated to the Early Holocene: In particular the moraine with the sample Göscheneralpsee was originally connected to the 'catastrophic glacier advance' of the Chelengletscher. Contrary to Zoller *et al*.'s (1966) observations, the direction and dip of the moraine indicate that the glacier ended in the western area of the lake and not close to the dam. Our dating results suggest that the surge hypothesis of Zoller *et al*.'s study (1966) should be rejected, because during the time period of the presumed Göschenen Cold Phases the glaciers could have only reached terminal positions up valley from our sampling sites (Fig. 3), which indicates that their extents were in the range of those mapped for the Little Ice Age.

The glaciological perspective on the Göschenen Cold Phases

Our new exposure ages derived from the Göscheneralp stage moraines contradict the theory of Zoller *et al*. (1966) and their interpretation of the borehole sediments as *in situ* till of a glacier advance during the Göschenen Cold Phase I at ~ 2.5 ka. We find clear indication that the moraines at the western shore of the Göscheneralpsee were deposited during the Early Holocene and have not been overridden by a subsequent glacier advance (Fig. 3). Consequently, Zoller *et al.*'s glaciological definition of Göschenen Cold Phase I as a distinct glacier surge reaching down to the dam area has to be abandoned. A local rockfall/mudflow or till reworking could possibly explain the observed borehole deposits. This alternative explanation was already considered by the authors themselves (Zoller *et al*. 1966). The geologic N-S profiles presented in the original study showed that rock deposits in the lake area are much thicker on the southern side of the valley. This relationship could indicate that the debris material originated from rockfall from the rather steep and block-rich north-facing slopes of the Feldschijen and the Mittagsstock (Fig. 1).

The ^{14}C-ages that originally defined the timing of the Göschenen Cold Phase I originated from samples below and above the presumed moraine in the borehole. The material below the supposed "moraine layer" was peaty silt (bulk sample of 20 cm) dated to ~2.8 ^{14}C ka (~3 cal. ka BP). Above the assumed moraine material, at a depth of 11 m, an *ex situ* piece of an *Alnus viridis* root was dated to ~2.3 ^{14}C ka (~2.3 cal. ka BP). Reworking of the root and an in-washing of the dated silty material into an older deposit cannot be excluded. The date of an *in situ Larix* stump that was sampled at a similar depth (12 m) in another pit with a ^{14}C-age of 3.3 ka (~3.5 cal. ka BP) was not included in Zoller *et al*.'s (1966) interpretation of local depositional events, because there was no direct stratigraphic connection to the debris layer observed in the other pit. Interestingly, Zoller's drillings also revealed peat at a depth of 25 m that was dated to ~8.8 ^{14}C ka (~9.8–10 cal. ka BP). The age of this peat matches relatively well the start of the formation of the mires in the roches moutonnées area on the northern side of the valley at the Brätschenflue site at 8.5 cal. ka BP (Fig. 3; Boxleitner *et al*. 2017). If this age is accurate, this would indicate that the valley floor became ice-free after the Younger Dryas - in accordance with the sequence of ^{10}Be-dated moraines presented in this study. Both the age constraints and the selective interpretation of the observed deposits in the original study appear to be questionable. While the definition of the Göschenen Cold Phase I is partly based on the presumptive moraine layer, the Göschenen Cold Phase II was entirely defined on the analysis of pollen data (Zoller *et al.* 1966).

Thus we must detach the glaciological from the pollen-based climatological definition of the Göschenen Cold Phases. While there is good evidence in the European Alps for the Göschenen Cold Phase I from pollen and dendrochronology studies (e.g. Gamper & Suter 1982; Burga *et al*. 2001), palynostratigraphic and palaeoclimatic signals for the Göschenen Cold Phase II are more uncertain, because they even in the Göschenertal increasingly overlap with evidence of vegetation changes triggered by human activity (Boxleitner *et al.* 2017). Uncertainties due to differential pollen production and dispersal of trees and herbs as well as due to human disturbance, e.g. lowering of the treeline because of logging and livestock production, since the Neolithic times often complicate the palaeoclimatic interpretation of pollen-based findings (Haas *et al*. 1998 and references therein). So even if the pollen signal suggests the existence of colder conditions, the original glaciological definition of the Göschenen Cold Phases as periods of glacier advances clearly exceeding the LIA maximum should be rejected.

Evidence from various studies (compilation in Ivy-Ochs *et al*. 2009) suggests that glaciers advanced during the Göschenen Cold Phases, but stayed either within the range of the LIA-extents or remained even smaller. A glacier advance slightly outside the LIA-limit was dated in the forefield of the nearby Steingletscher and attributed to Göschenen Cold Phase I (King 1974; Schimmelpfennig *et al*. 2014). Studies at the Aletsch glacier (Holzhauser *et al*. 2005) and at the Triftje- and Oberseegletscher in the Swiss Alps (Kronig *et al*. 2018), as well as in the forefield of Mer de Glace in the French Alps (Le Roy *et al*. 2015) showed that glaciers advanced during Göschenen Cold Phase II, but were in the range of the following LIA or remained smaller.

At the type locality, where the Göschenen Cold Phases have been defined, there is no evidence for pronounced glacier advances during the corresponding time period. The Göschenen Cold Phases have become a frequently cited feature of the Alpine Holocene climate history, while from our point of view the original study of Zoller *et al*. (1966) relies on a thin database and misconceptions about the glacier development. Over the years, the inherent uncertainties and methodological weaknesses of the original study were not adequately considered. As we show here, the local glaciers during the time period 3–1 ka, although they might have been advancing, most likely did not exceed their LIA extents.

Conclusions

Since the identification of the Göschenen Cold Phases as Late Holocene periods of climate cooling (Zoller *et al*. 1966) that affected both vegetation and glaciers, the Göschenertal in the central Swiss Alps became a prominent type locality within the framework of Alpine glacier history. Using ^{10}Be exposure dating, we dated moraines in order to reconstruct the local glacier development and re-assess the relations among glacier deposits at the type locality that led to the definition of the Göschenen Cold Phases. In particular, we wanted to investigate, if the assumed glacier advance linked to the Göschenen Cold Phase I (ca. 3–2.3 ka) in fact occurred.

Outside of the Little Ice Age (LIA) extent of the local glaciers we could date moraines belonging to two different stages. Moraines of the older stage indicate a glacier terminal position in the village of Göschenen (Göschenen stage). Boulders from these moraines were dated to the Younger Dryas, while younger moraines belonging to the second stage, up-valley to the west of the lake (Göscheneralp stage), were deposited during the Early Holocene. These results question earlier stadial attributions that were based on ELA- and ΔELA-calculations. The applicability of the AAR-method with a standard ratio of 0.67 for the chronological correlation of moraines of different glaciers and therefore the derivation of indirect age constraints appears to be debatable.

In addition, our dating results contradict the glaciological definition of the Göschenen Cold Phases: The supposed non-climatic glacier advance at ~2.5 ka with a terminal position in the eastern part of the lake seems to be a misinterpretation of the sedimentological results in Zoller *et al*.'s original study (1966), because the dated moraines further up valley have been deposited during the Early Holocene and have not been overridden by a glacier since then. The actual glacier extents at the type locality during the Göschenen Cold Phases remain unclear. Most likely glaciers were smaller or in the range of the LIA. While we do not have the data to re-evaluate the pollen-based palaeo-climatic definition of the Göschenen Cold Phases, we can clearly disprove that these periods were locally characterized by pronounced glacier advances exceeding the outlines of the Little Ice Age. From a glaciological perspective, the term Göschenen Cold Phases in the sense of a Late Holocene stadial or as a reference stage in moraine stratigraphies should therefore be abandoned. While there is plenty of evidence for the existence of Late Holocene cold phases, the Göschenen type locality and the corresponding nomenclature seem to be inappropriate for further referencing because of the inadequacies of the original study.

Data availability. – The input data for the calculation of the exposure ages are available in the Supplement (Table S1).

Competing interests. – The authors declare that they have no conflict of interest.

Acknowledgements. – We are thankful for the help of Felix Renner, Kseniia Ashastina and Alessandra Musso during fieldwork and would like to thank the Ion Beam Physics group of the ETHZ for the AMS measurements. Also we gratefully acknowledge the helpful comments of two anonymous reviewers.

Author contributions. – M. Boxleitner contributed to the study concept, organised and performed the fieldwork, prepared the samples for the AMS measurements, calculated exposure ages and ELAs, analysed and interpreted the data and wrote the manuscript; S. Ivy-Ochs helped with the data interpretation and manuscript preparation; M. Egli contributed to the study concept, the data analysis and

manuscript preparation; D. Brandova helped with the lab work and exposure age calculation; M. Christl took the AMS measurements; D. Dahms gave support during field work and with the writing of the article; M. Maisch contributed to the study concept, the field work, data interpretation and manuscript preparation.

References

André, M. 2002: Rates of postglacial rock weathering on glacially scoured outcrops (abisko–riksgränsen area, 68°n). *Geografiska Annaler: Series A, Physical Geography 84*, 139–150.

Balco, G., Briner, J., Finkel, R. C., Rayburn, J. A., Ridge, J. C. & Schaefer, J. M. 2009: Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology 4*, 93–107.

Balco, G., Stone, J. O., Lifton, N. A. & Dunai, T. J. 2008: A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology 3*, 174–195.

Benn, D. I. & Lehmkuhl, F. 2000: Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. *Quaternary International 65*, 15–29.

Bichler, M. G., Reindl, M., Reitner, J. M., Drescher‐Schneider, R., Wirsig, C., Christl, M., Hajdas, I. & Ivy‐Ochs, S. 2016: Landslide deposits as stratigraphical markers for a sequence‐based glacial stratigraphy: a case study of a Younger Dryas system in the Eastern Alps. *Boreas 45*, 537–551.

Böhlert, R., Egli, M., Maisch, M., Brandová, D., Ivy-Ochs, S., Kubik, P. W. & Haeberli, W. 2011: Application of a combination of dating techniques to reconstruct the Lateglacial and early Holocene landscape history of the Albula region (eastern Switzerland). *Geomorphology 127*, 1–13.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J. & Stone, J. 2016: Geological calibration of spallation production rates in the CRONUS-Earth project. *Quaternary Geochronology 31*, 188–198.

Bortenschlager, S. & Patzelt, G. 1969: Wärmezeitliche Klima- und Gletscherschwankungen im Pollenprofil eines hochgelegenen Moores (2270 m) der Venedigergruppe. *Eiszeitalter und Gegenwart 20,* 10–31.

Boxleitner, M., Musso, A., Waroszewski, J., Malkiewicz, M., Maisch, M., Dahms, D., Brandová, D., Christl, M., de Castro Portes, R. & Egli, M. 2017: Late Pleistocene – Holocene surface processes and landscape evolution in the central Swiss Alps. *Geomorphology 295*, 306–322.

Burga, C. A., Perret, R. & Vonarburg, C. 1998: *Vegetation und Klima der Schweiz seit dem jüngeren Eiszeitalter*. 805 pp. Ott Verlag, Thun.

Burga, C. A., Perret, R. & Zoller, H. 2001: Swiss localities of early recognized Holocene climate fluctuations - Characterization and significance. *Viertelsjahresschrift der Naturforschenden Gesellschaft in Zürich 146*, 65–74.

Charpentier Ljungqvist, F. 2011: The spatio-temporal pattern of the mid-Holocene thermal maximum. *Geografie–Sborník ČGS 116*, 91–110.

Chmeleff, J., von Blanckenburg, F., Kossert, K. & Jakob, D. 2010: Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268*, 192–199.

Christl, M., Vockenhuber, C., Kubik, P. W., Wacker, L., Lachner, J., Alfimov, V. & Synal, H.-A. 2013: The ETH Zurich AMS facilities: Performance parameters and reference materials. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 294*, 29–38.

Clark, D. H., Clark, M. M. & Gillespie, A. R. 1994: Debris-covered glaciers in the Sierra Nevada, California, and their implications for snowline reconstructions. *Quaternary Research 41*, 139–153.

Claude, A., Ivy-Ochs, S., Kober, F., Antognini, M., Salcher, B. & Kubik, P. 2014: The Chironico landslide (Valle Leventina, southern Swiss Alps): age and evolution. *Swiss Journal of Geosciences 107*, 273–291.

Federici, P. R., Granger, D. E., Pappalardo, M., Ribolini, A., Spagnolo, M. & Cyr, A. J. 2008: Exposure age dating and Equilibrium Line Altitude reconstruction of an Egesen moraine in the Maritime Alps, Italy. *Boreas 37*, 245–253.

Gamper, M. & Suter, J. 1982: Postglaziale Klimageschichte der Schweizer Alpen. *Geographica Helvetica 37*, 105–114.

Goehring, B. M., Schaefer, J. M., Schluechter, C., Lifton, N. A., Finkel, R. C., Jull, A. T., Akçar, N. & Alley, R. B. 2011: The Rhone Glacier was smaller than today for most of the Holocene. *Geology 39*, 679–682.

Gosse, J. C. & Phillips, F. M. 2001: Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews 20*, 1475–1560.

Gross, G., Kerschner, H. & Patzelt, G. 1977: Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. *Zeitschrift für Gletscherkunde und Glazialgeologie 12*, 223–251.

Grove, J. M. 1988: The Little Ice Age. 520 pp. Routledge, London.

Haas, J. N., Richoz, I., Tinner, W. & Wick, L. 1998: Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. *The Holocene 8*, 301–309.

Heyman, J. 2014: Paleoglaciation of the Tibetan Plateau and surrounding mountains based on exposure ages and ELA depression estimates. *Quaternary Science Reviews 91*, 30–41.

Holzhauser, H. 1995: Gletscherschwankungen innerhalb der letzten 3200 Jahre am Beispiel des grossen Aletsch-und des Gornergletschers. Neue Ergebnisse. *Gletscher im ständigen Wandel 6*, 101–123.

Holzhauser, H., Magny, M. & Zumbühl, H. J. 2005: Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene 15*, 789–801.

Holzhauser, H. & Zumbühl, H. J. 1988: Alpengletscher in der Kleinen Eiszeit. *Die Alpen 64,* 129–322.

Hormes, A., Müller, B. U. & Schlüchter, C. 2001: The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *The Holocene 11*, 255–265.

Ivy-Ochs, S. 2015: Glacier variations in the European Alps at the end of the last glaciation. *Cuadernos de investigación geográfica 41*, 295–315.

Ivy-Ochs, S. & Kober, F. 2008: Surface exposure dating with cosmogenic nuclides. *Quaternary Science Journal 57*, 157–189.

Ivy-Ochs, S., Schlüchter, C., Kubik, P. W., Synal, H.-A., Beer, J. & Kerschner, H. 1996: The exposure age of an Egesen moraine at Julier Pass, Switzerland, measured with the cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{36}Cl. *Eclogae Geologicae Helvetiae 89*, 1049–1064.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W. & Schlüchter, C. 2009: Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews 28*, 2137–2149.

Joerin, U. E., Stocker, T. F. & Schlüchter, C. 2006: Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene 16*, 697–704.

Kelly, M. A., Kubik, P. W., von Blanckenburg, F. & Schlüchter, C. 2004: Surface exposure dating of the Great Aletsch Glacier Egesen moraine system, western Swiss Alps, using the cosmogenic nuclide ^{10}Be. *Journal of Quaternary Science 19*, 431–441.

Kerschner, H. 2009: *Gletscher und Klima im Alpinen Spätglazial und frühen Holozän*. In Schmidt, R., Matulla, C., Psenner, R. (eds.), Klimawandel in Österreich. Die letzten 20,000 Jahre und ein Blick voraus. 5–26 pp. Innsbruck University Press, Innsbruck.

King, L. 1974: *Studien zur postglazialen Gletscher-und Vegetationsgeschichte des Sustenpassgebietes*. 123 pp. Helbing & Lichtenhahn, Basel.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U. C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G. & von Gostomski, C. L. 2010: A new value for the half-life of ^{10}Be by heavy-ion elastic recoil detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268*, 187–191.

Kronig, O., Ivy-Ochs, S., Hajdas, I., Christl, M., Wirsig, C. & Schlüchter, C. 2018: Holocene evolution of the Triftje- and the Oberseegletscher (Swiss Alps) constrained with ^{10}Be exposure and radiocarbon dating. *Swiss Journal of Geosciences 111*, 117–131.

Labhart, T. & Pfiffner, O. A. 2011: *Geologische Karte des Kantons Uri.* Naturforschende Gesellschaft Uri, Altdorf.

Lal, D. 1991: Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. *Earth and Planetary Science Letters 104*, 424–439.

Le Roy, M., Deline, P., Carcaillet, J., Schimmelpfennig, I., Ermini, M. & Team, A. 2017: ^{10}Be exposure dating of the timing of Neoglacial glacier advances in the Ecrins-Pelvoux massif, southern French Alps. *Quaternary Science Reviews 178*, 118–138.

Le Roy, M., Nicolussi, K., Deline, P., Astrade, L., Edouard, J.-L., Miramont, C. & Arnaud, F. 2015: Calendar-dated glacier variations in the western European Alps during the Neoglacial: the Mer de Glace record, Mont Blanc massif. *Quaternary Science Reviews 108*, 1–22.

Leemann, A. & Niessen, F. 1994: Holocene glacial activity and climatic variations in the Swiss Alps: reconstructing a continuous record from proglacial lake sediments. *The Holocene 4*, 259–268.

Luetscher, M., Hoffmann, D. L., Frisia, S. & Spötl, C. 2011: Holocene glacier history from alpine speleothems, Milchbach cave, Switzerland. *Earth and Planetary Science Letters 302*, 95–106.

Lukas, S. 2007: Early-Holocene glacier fluctuations in Krundalen, south central Norway: palaeoglacier dynamics and palaeoclimate. *The Holocene 17*, 585–598.

Maisch, M. 1981: *Glazialmorphologische und gletschergeschichtliche Untersuchungen im Gebiet zwischen Landwasser- und Albulatal (Kt. Graubünden)*. 215 pp. Universität Zürich, Zürich.

Meier, M. F. & Post, A. S. 1962: Recent variations in mass net budgets of glaciers in western North America. *International Association of Hydrological Sciences Publication 58*, 63–77.

Moran, A. P., Ivy-Ochs, S., Christl, M. & Kerschner, H. 2017: Exposure dating of a pronounced glacier advance at the onset of the late-Holocene in the central Tyrolean Alps. *The Holocene 27*, 1350–1358.

Moran, A. P., Kerschner, H. & Ivy-Ochs, S. 2016: Redating the moraines in the Kromer Valley (Silvretta Mountains) – New evidence for an early Holocene glacier advance. *The Holocene 26*, 655–664.

Nicolussi, K & Patzelt, G. 2001: Untersuchungen zur holozänen Gletscherentwicklung von Pasterze und Gepatschferner (Ostalpen). *Zeitschrift für Gletscherkunde und Glazialgeologie 36*, 1–87.

Nicolussi, K. & Schlüchter, C. 2012: The 8.2 ka event—Calendar-dated glacier response in the Alps. *Geology 40*, 819–822.

Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C. & McAninch, J. 2007: Absolute calibration of ^{10}Be AMS standards. *Nuclear*

Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 258, 403–413.

Osmaston, H. 2005: Estimates of glacier equilibrium line altitudes by the Area×Altitude, the Area×Altitude Balance Ratio and the Area×Altitude Balance Index methods and their validation. *Quaternary International 138–139*, 22–31.

Porter, S. C. 1975: Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quaternary Research 5*, 27–47.

Reitner, J., Ivy-Ochs, S., Drescher-Schneider, R., Hajdas, I. & Linner, M. 2016: Reconsidering the current stratigraphy of the Alpine Lateglacial: Implications of the sedimentary and morphological record of the Lienz area (Tyrol/Austria). *E&G Quaternary Science Journal 65*, 113–144.

Renner, F.B. 1982: *Beiträge zur Gletschergeschichte des Gotthardgebietes und dendroklimatologische Analysen an fossilen Hölzern.* 180 pp. Universität Zürich, Zürich.

Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H. & Fichefet, T. 2009: The spatial and temporal complexity of the Holocene thermal maximum. *Nature Geoscience 2*, 411–414.

Röthlisberger, H. 1969: Evidence for an ancient glacier surge in the Swiss Alps. *Canadian Journal of Earth Sciences 6*, 863–865.

Schimmelpfennig, I., Schaefer, J. M., Akçar, N., Ivy-Ochs, S., Finkel, R. C. & Schlüchter, C. 2012: Holocene glacier culminations in the Western Alps and their hemispheric relevance. *Geology 40*, 891–894.

Schimmelpfennig, I., Schaefer, J. M., Akçar, N., Koffman, T., Ivy-Ochs, S., Schwartz, R., Finkel, R. C., Zimmerman, S. & Schlüchter, C. 2014: A chronology of Holocene and Little Ice Age glacier culminations of the Steingletscher, Central Alps, Switzerland, based on high-sensitivity beryllium-10 moraine dating. *Earth and Planetary Science Letters 393*, 220–230.

Schindelwig, I., Akçar, N., Kubik, P. W. & Schlüchter, C. 2012: Lateglacial and early Holocene dynamics of adjacent valley glaciers in the Western Swiss Alps. *Journal of Quaternary Science 27*, 114–124.

Schneebeli, W. & Röthlisberger, F. 1976: 8000 Jahre Walliser Gletschergeschichte. Ein Beitrag zur Erforschung des Klimaverlaufs in der Nacheiszeit. 152 pp. Verlag Schweizer Alpen-Club, Bern.

Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., Nesje, A., Owen, L. A., Wanner, H., Wiles, G. C. & Young, N. E. 2015: Holocene glacier fluctuations. *Quaternary Science Reviews 111*, 9–34.

Spillmann, P., Labhart, T., Brückner, W., Renner, F., Gisler, C. & Zgraggen, A. 2011: *Geologie des Kantons Uri*. 224 pp. Naturforschende Gesellschaft Uri, Altdorf .

Stone, J. O. 2000: Air pressure and cosmogenic isotope production. *Journal of Geophysical Research: Solid Earth 105*, 23753–23759.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F. & Kaplan, J. O. 2008: Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews 27*, 1791–1828.

Wipf, A. 2001: Gletschergeschichtliche Untersuchungen im spät-und postglazialen Bereich des Hinteren Lauterbrunnentals (Berner Oberland, Schweiz). *Geographica Helvetica 56*, 133–144.

Zienert, A. 1970: Würm-Rückzugsstadien vom Schwarzwald bis zur Hohen Tatra. *Eiszeitalter und Gegenwart 21, 58–70*.

Zienert, A. 1965: Gran Paradiso—Mont Blanc: Prähistorische und historische Gletscherstände. *Eiszeitalter und Gegenwart 16,* 202–225.

Zoller, H., Schindler, C. M. & Röthlisberger, H. 1966: Postglaziale Gletscherstände und Klimaschwankungen im Gotthardmassiv und Vorderrheingebiet. *Verhandlungen der Naturforschenden Gesellschaft in Basel 77*, 97–164.

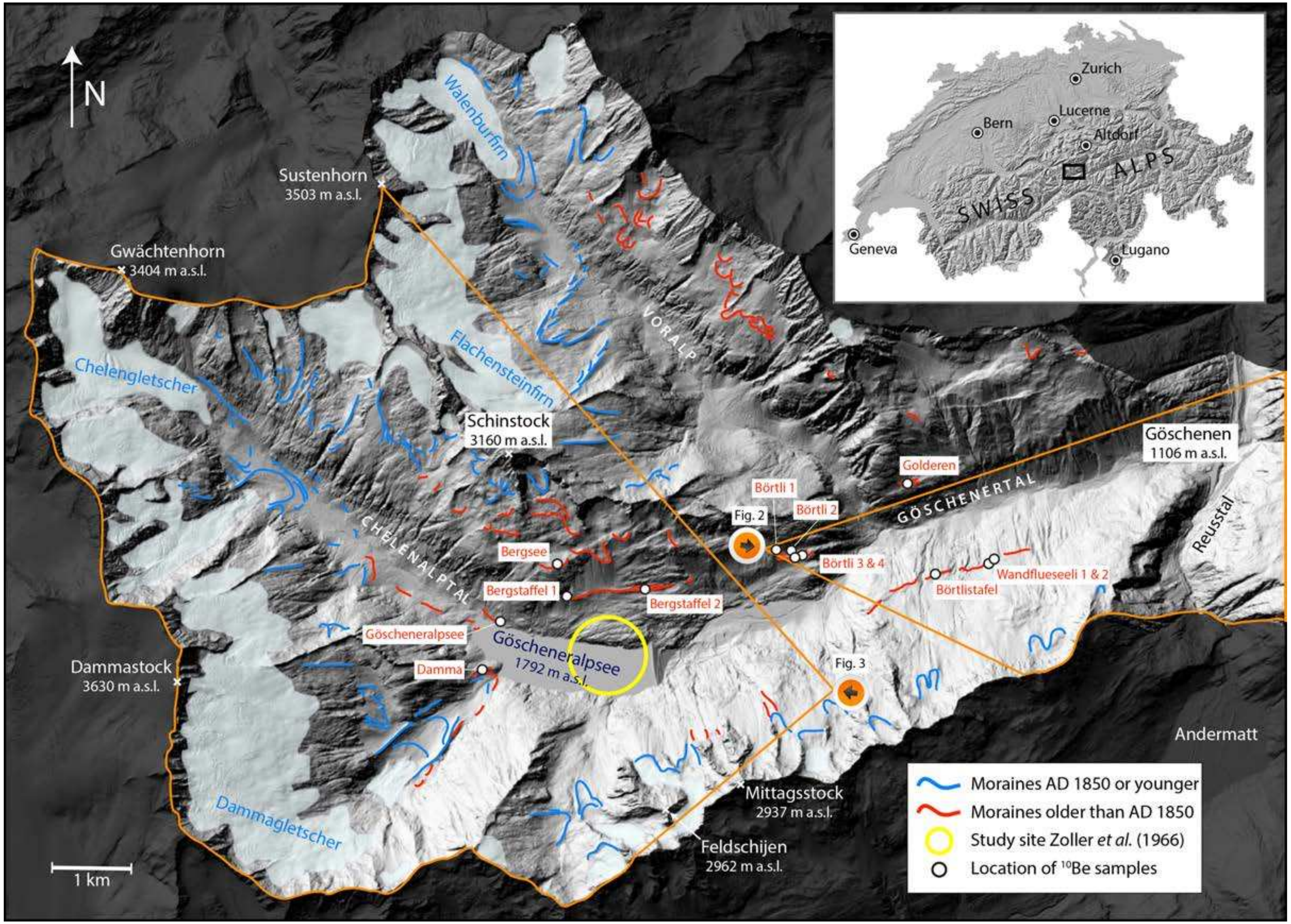
Figure Captions

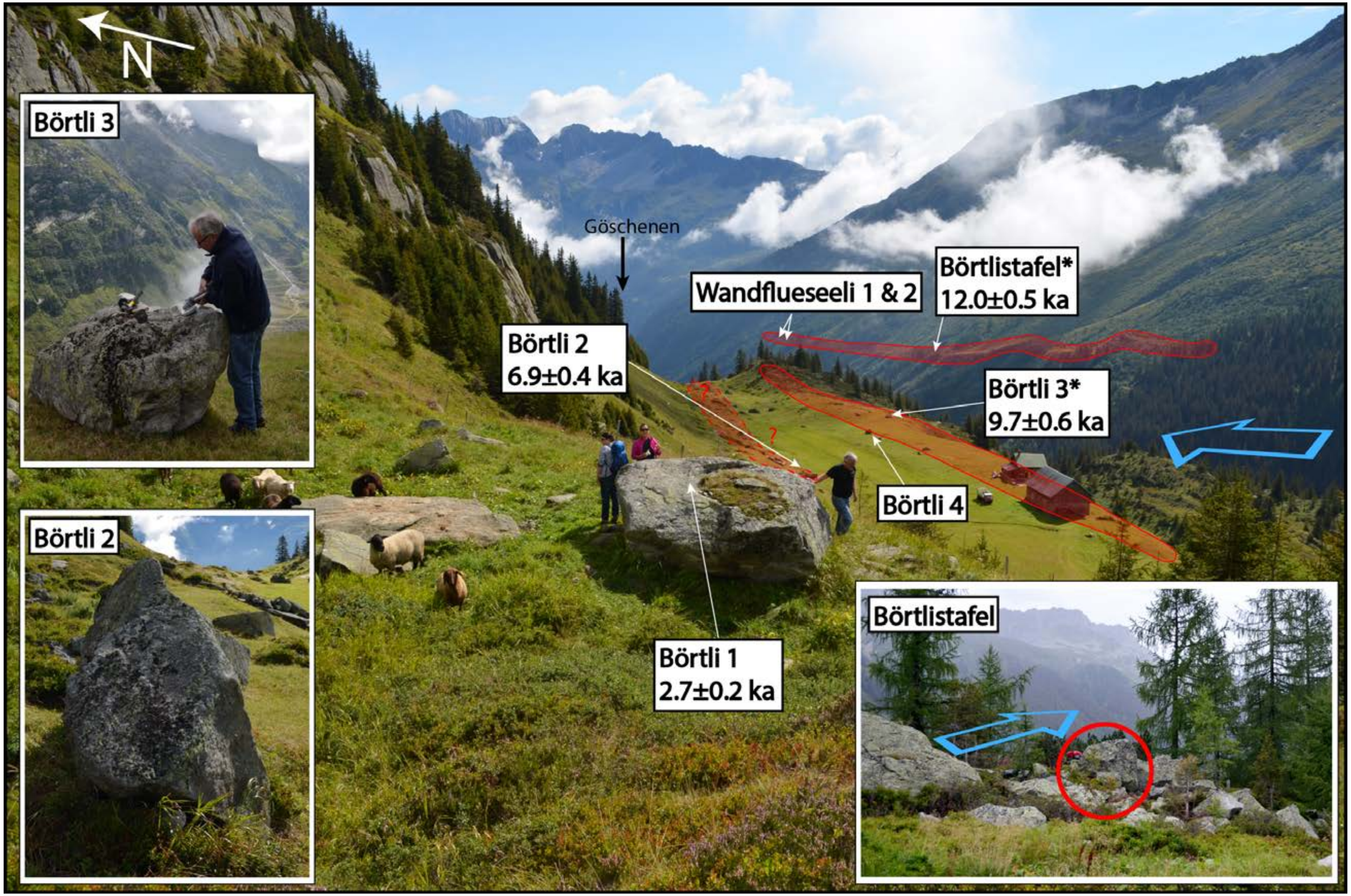
Fig. 1
Overview of the Göschenertal. The inset map shows the location within Switzerland. The arrows and outlines display the perspective and areas shown in Figs 2 and 3. Reproduced by permission of swisstopo (BA18060).

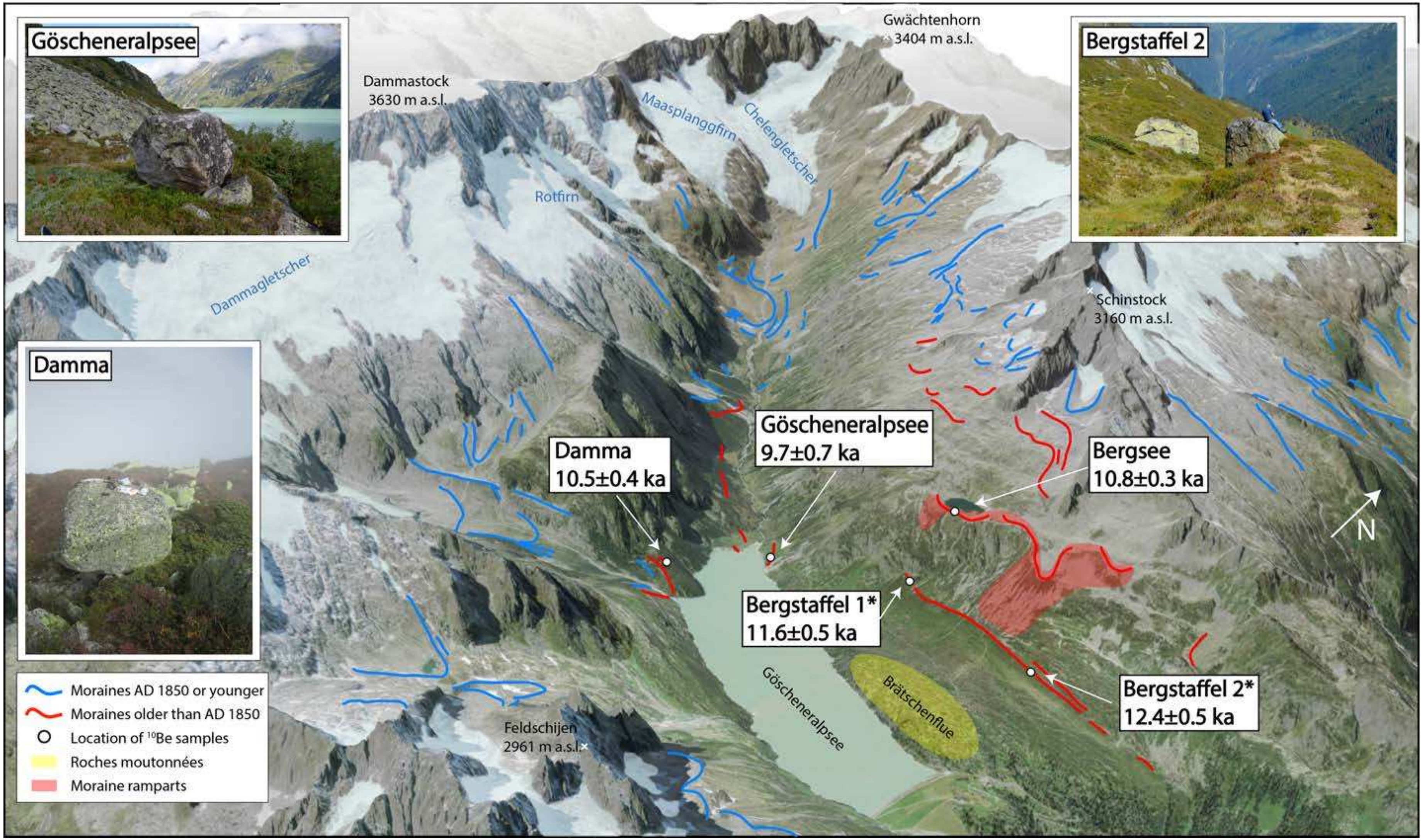
Fig. 2
Photograph of the lower Göschenertal with moraines (red) and sample locations. The origin of the outer embankment at the Börtli site remains ambiguous (dashed line and question marks). Boulders Börtli 4 and Wandflueseeli 1 and 2 could not be dated because of too little quartz in the rock material. The blue arrow indicates the flow direction of the glacier. * = Data recalculated from Boxleitner *et al*. (2017).

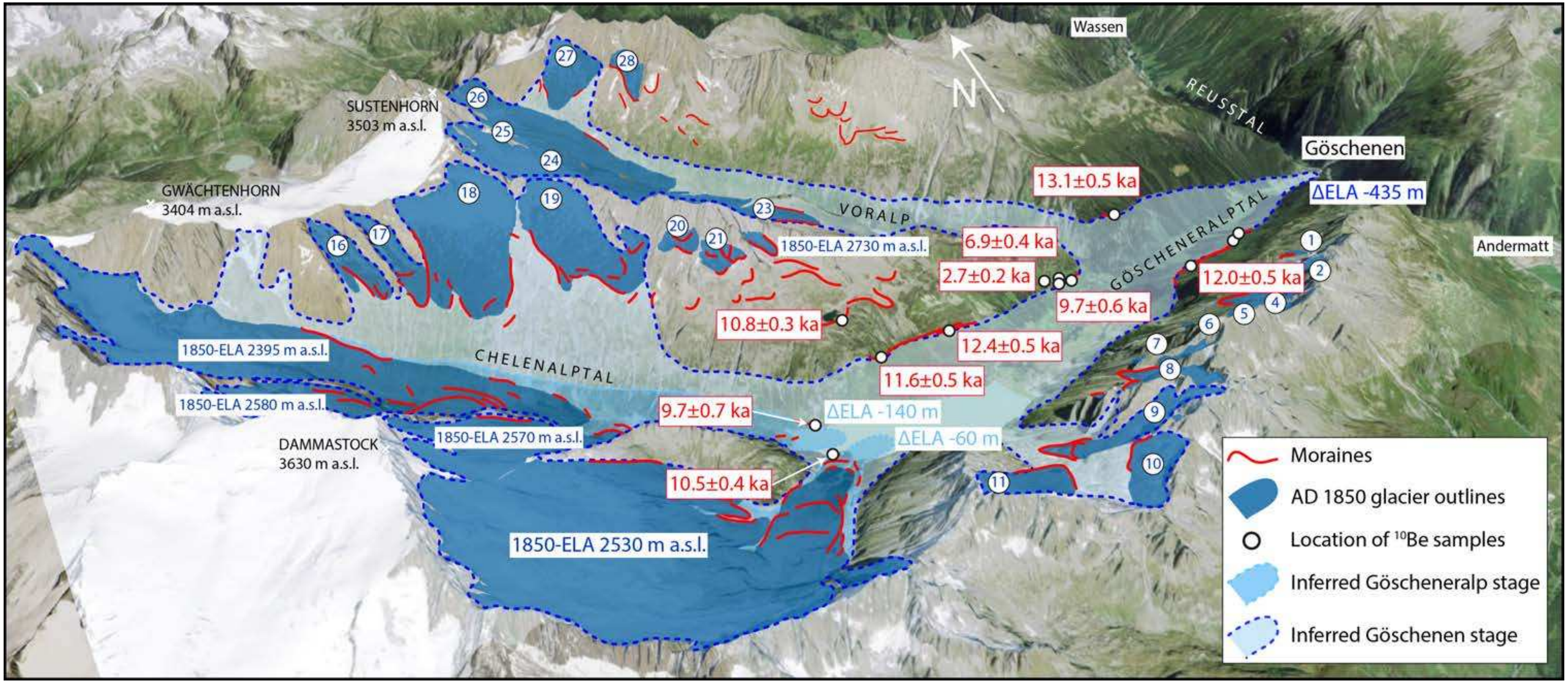
Fig. 3
View of the upper Göschenertal with the Chelenalptal and Dammagletscher forefield. * = Data recalculated from Boxleitner *et al*. (2017). Reproduced by permission of swisstopo (BA18060).

Fig. 4
Reconstructed glacier extents of AD 1850, the Göscheneralp stage and the Göschenen stage. Displayed (inferred) outlines were used for ELA and ΔELA calculation. The question mark indicates the unclear stage attribution of the Bergsee moraines. Numbering of the glaciers corresponds to Table 2. Reproduced by permission of swisstopo (BA18060).


N
Sustenhorn
3503 m a.s.l.
Gwächtenhorn
3404 m a.s.l.
Walenburfirn
Flachensteinfirn
Chelengletscher
VORALP
Schinstock
3160 m a.s.l.
Göschenen
1106 m a.s.l.
GÖSCHENERTAL
CHELENALPTAL
Golderen
Börtli 1
Börtli 2
Fig. 2
Börtli 3 & 4
Bergsee
Bergstaffel 1
Bergstaffel 2
Börtlistafel
Wandflueseeli 1 & 2
Reusstal
Göscheneralpsee
Göscheneralpsee
1792 m a.s.l.
Damma
Dammastock
3630 m a.s.l.
Fig. 3
Andermatt
Mittagsstock
2937 m a.s.l.
Feldschijen
2962 m a.s.l.
Dammagletscher
1 km
Moraines AD 1850 or younger
Moraines older than AD 1850
Study site Zoller et al. (1966)
Location of 10Be samples
Zurich
Bern
Lucerne
Altdorf
SWISS ALPS
Geneva
Lugano


N
Börtli 3
Göschenen
Börtlistafel*
12.0±0.5 ka
Wandflueseeli 1 & 2
Börtli 2
6.9±0.4 ka
Börtli 3*
9.7±0.6 ka
Börtli 4
Börtli 2
Börtli 1
2.7±0.2 ka
Börtlistafel


Göscheneralpsee
Bergstaffel 2
Damma
Gwächtenhorn
3404 m a.s.l.
Dammastock
3630 m a.s.l.
Maasplanggfirn
Chelengletscher
Rotfirn
Dammagletscher
Schinstock
3160 m a.s.l.
Göscheneralpsee
9.7±0.7 ka
Damma
10.5±0.4 ka
Bergsee
10.8±0.3 ka
N
Bergstaffel 1*
11.6±0.5 ka
Bergstaffel 2*
12.4±0.5 ka
Göscheneralpsee
Brätschenflue
Feldschijen
2961 m a.s.l.
Moraines AD 1850 or younger
Moraines older than AD 1850
Location of 10Be samples
Roches moutonnées
Moraine ramparts



Wassen
N
REUSSTAL
Göschenen
ΔELA -435 m
Andermatt
SUSTENHORN
3503 m a.s.l.
GWÄCHTENHORN
3404 m a.s.l.
VORALP
GÖSCHENERALPTAL
13.1±0.5 ka
6.9±0.4 ka
2.7±0.2 ka
9.7±0.6 ka
12.0±0.5 ka
10.8±0.3 ka
12.4±0.5 ka
11.6±0.5 ka
1850-ELA 2730 m a.s.l.
1850-ELA 2395 m a.s.l.
CHELENALPTAL
1850-ELA 2580 m a.s.l.
1850-ELA 2570 m a.s.l.
DAMMASTOCK
3630 m a.s.l.
9.7±0.7 ka
ΔELA -140 m
ΔELA -60 m
10.5±0.4 ka
1850-ELA 2530 m a.s.l.
Moraines
AD 1850 glacier outlines
Location of ^{10}Be samples
Inferred Göscheneralp stage
Inferred Göschenen stage

Table 1. Exposure ages of the sampled boulders. The samples are sorted from down-valley to up-valley. Latitude and longitude are in WGS84 coordinates. Shielding correction includes the effects caused by mountain topography, dip and strike of the various boulder surfaces. Rock density is 2.7 g cm^{-3} throughout. Exposure ages are calculated with the NENA production rate and an erosion rate of 1 mm ka^{-1}. The input data for the age calculation can be found in Table S1.

Nr.	Sample name	Lat.	Long.	Elevation	Lithology	Thickness	Shielding factor	Quartz	Carrier	^{10}Be[1]	Exposure age
		(°N)	(°E)	(m a.s.l.)		(cm)		(g)	(mg)	(10^3 atoms g^{-1})	(a)
1	Börtlistafel[2]	46.655	8.544	1649	Granite	2	0.966	31.53	0.351	177.68±7.23	12 040±500
2	Golderen[2]	46.665	8.540	1746	Granite	3	0.952	31.08	0.351	202.97±7.27	13 100±480
3	Börtli 3[2]	46.658	8.522	1803	Gneiss	6	0.956	31.34	0.341	154.10±8.88	9700±570
4	Börtli 2	46.658	8.521	1807	Granite	4	0.930	30.17	0.353	109.63±5.95	6940±380
5	Börtli 1	46.658	8.518	1855	Gneiss	2.5	0.924	32.66	0.349	45.30±3.79	2740±230
6	Bergstaffel 2[2]	46.654	8.495	2034	Gneiss	3	0.977	30.65	0.353	243.72±8.63	12 440±450
7	Bergstaffel 1[2]	46.653	8.484	2091	Granite	3	0.919	30.53	0.350	223.12±9.13	11 620±480
8	Bergsee	46.657	8.483	2348	Granite	2	0.984	31.16	0.352	267.19±7.90	10 790±320
9	Damma	46.645	8.470	1887	Gneiss	1.5	0.951	30.41	0.352	182.43±6.31	10 470±370
10	Göscheneralpsee	46.651	8.473	1809	Granite	2.5	0.925	30.46	0.344	154.85±10.17	9740±650

[1] AMS measurements errors are at the 1σ level, including the statistical (counting) error and the error due to normalization to standards (07KNSTD) and blanks.
[2] Data recalculated from Boxleitner *et al*. (2017); CRONUS version 2.3 results in ~2.5–3 % younger ages.

Table 2. Equilibrium Line Altitudes (ELAs) and ELA depression values (ΔELAs) in comparison to 1850; highlighted fields mark glaciers that contributed to Göschenen stage glaciation. NL = Nameless.

Nr.	Glacier	1850 ELA (m a.s.l.)	GA-S[1] ELA (m a.s.l.)	ΔELA (m)	G-S[2] ELA (m a.s.l.)	ΔELA (m)
1	NL1	2380				
2	NL2	2630				
3	NL3	2450				
4	Mittagsgletscher	2565				
5	NL4	2455				
6	NL5	2505				
7	NL6	2375				
8	Zandgletscher	2560				
9	Blauberggletscher	2655				
10	Älprigengletscher	2755				
11	Rundfirn	2690				
12	Dammagletscher	2530	2470	- 60		
13	Rotfirn	2565				
14	Mässplanggstock	2580	2305	- 140	2110	- 435
15	Chelengletscher	2395				
16	Rotstock W	2775				
17	Rotstock O	2735				
18	Brunnenfirn W	2775				
19	Brunnenfirn O	2775				
20	NL7	2850				
21	NL8	2775				
22	NL9 Schinstockgletscher	2730	2505[3]	- 225[3]		
23	Stockgletscher	2650				
24	Flächensteinfirn	2580				
25	Brunnenfirn S	2660				
26	Walenburfirn S	2465				
27	Hangfirn	2785				
28	NL10	2840				

[1]Göscheneralp stage.
[2]Göschenen stage.
[3]Assumed affiliation to Göscheneralp stage.

Table S1. Input data used for the online exposure age calculation (http://hess.ess.washington.edu/math/).

Lab. ID	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Pressure flag	Sample thickness (cm)	Density (g cm^{-3})	Shielding factor	Erosion rate (cm a^{-1})	^{10}Be content (rounded) (atoms g^{-1})	Uncertainty in ^{10}Be (atoms g^{-1})	Be AMS standard	^{26}Al content (atoms g^{-1})	Uncertainty in ^{26}Al (atoms g^{-1})	Al AMS standard
Boertli1	46.66	8.52	1855	std	2.5	2.7	0.924	0.0001	45301	3794	07KNSTD	0	0	KNSTD
Boertli2	46.66	8.52	1807	std	4	2.7	0.930	0.0001	109634	5953	07KNSTD	0	0	KNSTD
Boertli3	46.66	8.52	1803	std	6	2.7	0.956	0.0001	154103	8884	07KNSTD	0	0	KNSTD
Boertlistafel	46.66	8.54	1649	std	2	2.7	0.966	0.0001	177681	7225	07KNSTD	0	0	KNSTD
Goe-Alpsee	46.65	8.47	1809	std	2.5	2.7	0.925	0.0001	154847	10 166	07KNSTD	0	0	KNSTD
Bergstaffel1	46.65	8.48	2091	std	3	2.7	0.918	0.0001	223124	9125	07KNSTD	0	0	KNSTD
Bergstaffel2	46.65	8.50	2034	std	3	2.7	0.977	0.0001	243720	8632	07KNSTD	0	0	KNSTD
Bergsee	46.66	8.48	2348	std	2	2.7	0.984	0.0001	267191	7903	07KNSTD	0	0	KNSTD
Damma	46.65	8.47	1887	std	1.5	2.7	0.951	0.0001	182428	6305	07KNSTD	0	0	KNSTD
Golderen	46.67	8.54	1746	std	3	2.7	0.952	0.0001	202966	7273	07KNSTD	0	0	KNSTD